

# The solar rotation in the period 1853–1870 from the sunspot catalogues of Carrington, Peters, and de la Rue

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**Abstract** R. C. Carrington, C. H. F. Peters, and W. de la Rue observed the sunspots in the second half of the 19th century, determining their heliographic positions between 1853 and 1870, before the establishment of the solar program of the Royal Greenwich Observatory. The large tables of sunspot positions included in the catalogues published by these observers have recently been converted to a machine readable format. The present work analyses this data by calculating the sunspot group velocities for each observer. These results are then fitted with a differential rotation law to compare the data of the three observers with each other and with the results published by other authors. Finally, a study is made of the possible relationship between the sunspot group areas as determined by de la Rue and the corresponding sunspot group velocities.

**Keywords:** Solar Rotation; Sunspot Areas.

## 1. Introduction

The recovery of old solar observations lets one to extend time series of various solar parameters into the past, including solar diameter, sunspot number, sunspot areas, and even sunspot positions. Sets of observations made during the same time period allow gaps to be filled, and provide either confirmation or reasonable doubt of the reliability of those data. In addition, with these historical data, one can see how these parameters change with time (Vaquero and Vázquez, 2009).

The telescopic observation of the Sun began in 1610 with the records of the English astronomer Thomas Harriot, who was followed by other pioneers. In the following decades and centuries, until the digital era, large amounts of solar data was collected, and is now preserved in libraries and archives. This data is gradually been recovered, digitalized, and analysed with current technology

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(Vaquero and Vázquez, 2009). In the last few years, for instance, several software packages have been developed to analyse sunspot drawings. Examples are HSunspots (Cristo, Vaquero, and Sánchez-Bajo, 2011), DigiSun (Clette, 2011), and CAMS (Cakmak, 2014).

Scans of the solar disk drawings made by the early solar observers in the first half of the 17th century, Thomas Harriot (Shirley, 1983), Galileo Galilei (Galilei, 1613), Christopher Scheiner (Scheiner, 1630), and Johannes Hevelius (Hevelius, 1647), have allowed the sunspots' heliographic positions to be determined and, from them, the rotation velocities of the groups (Eddy, Gilman, and Trotter, 1977; Herr, 1978; Sakurai, 1980; Herr, 1980; Abarbanell and Wöhl, 1981; Yallop *et al.*, 1982; Casas, Vaquero, and Vázquez, 2006). For the second half of the 17th century, during the Maunder Minimum (1645–1715), a period of low solar activity (Eddy, 1976; Vaquero and Trigo, 2015), just some isolated observations have been located with which to estimate the rotation velocities of the sunspot groups. Two examples are the cases of Nicholas Bion in 1672 (Casas, Vaquero, and Vázquez, 2006) and John Flamsteed in 1684 (Vaquero, Sánchez-Bajo, and Gallego, 2002). There is also a long series recorded by observers at the Paris Observatory which was recovered and analysed by Ribes and Nesme-Ribes (1993).

The sunspot drawings made by Johann Staudach in the period 1749–1799 were used by Arlt and Fröhlich (2012) to determine the solar differential rotation in the second half of the 18th century. There is only very sparse information about the solar rotation during the first half of the 19th century, especially during the Dalton Minimum (1800–1825). Sánchez-Bajo, Vaquero, and Gallego (2010) presented an estimate of solar rotation rate in the period 1847–1849 using the sunspot positions recorded by W. C. Bond at the Harvard College Observatory. Moreover, Arlt (2011) presented an inventory of the log books of Samuel Heinrich Schwabe, the discoverer of the solar cycle, and an evaluation of the solar drawings contained in this source from 1825–1867. Recently, Arlt *et al.* (2013) reported the heliographic coordinates determined from those solar drawings.

In the second half of the 19th century, long solar observation campaigns were conducted by Richard C. Carrington (Carrington, 1863), Gustav Spörer (Spörer, 1874), Christian F. H. Peters (Peters, 1907), Warren de la Rue (de la Rue, Steward, and Loewy, 1869 and 1870), and the Greenwich Observatory (Willis *et al.*, 2013). Lepshokov, Tlatov, and Vasil'eva, (2012) reconstructed the sunspots' characteristics using the data of Carrington and Spörer. Recently, Casas and Vaquero (2014) (CV14 hereafter) have described the conversion to machine readable format of the large tables of sunspot positions observed by Carrington, Peters and de la Rue, making a first analysis of the datasets. We have now determined the rotational speed of the Sun using the different sunspots as tracers to exploit this old data and we have established a differential rotation law for each observational dataset.

Our interest in this analysis was twofold. First, we wanted to check the evolution of the differential rotation law over short times. And second, we used the sunspot area data published by de la Rue to search for a correlation with the rotation velocity of the sunspot groups.

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## 2. Data

CV14 have provided an electronic version of the sunspot position catalogues made by Carrington, Peters, and de la Rue, taking into consideration the different coordinate systems that were used. Carrington and de la Rue used normalized polar coordinates  $(r, \theta)$  and the "Carrington" heliographic coordinates for each observation. This allowed a cross check to be made between them, revealing some typographical errors in the original papers (see CV14 for details). A calculation mistake was found in the data published by de la Rue, Steward, and Loewy (1870) because the  $B_0$  correction was not used in the published original data. Peters (1907) represented the sunspot positions in celestial Cartesian coordinates  $(\Delta\alpha, \Delta\delta)$  and in the "Peter" heliographic coordinates. In the same paper (Peters, 1907), a table compiled by Mr Philip Fox helps to transform the "Peters" coordinates to the "Carrington" coordinates. This again allowed us to do a cross check of the data and to correct some typographical errors.

A consistent dataset is required for all the data to be analysed. For this reason, we used the file **comdata.dat** introduced in our previous paper (CV14). In this file, the sunspot positions are given referred to the Carrington heliographic coordinates calculated from the polar and Cartesian coordinates listed by the three historical sources, and using the Sun's physical ephemeris provided on the *Horizons* Web page<sup>1</sup> (Giorgini *et al.*, 1996).

We use quotes in the name of the original Carrington coordinates because we found a systematic difference between them and the coordinates that we calculated. We do not know the origin of this difference, but believe it to be related to the ephemeris (see details in CV14).

## 3. Sunspot position cross-correlation

Carrington and de la Rue identified the sunspot groups with a sequential number, trying to relate their observations on different days. But there are some incongruences in the data. For this reason we created an algorithm to cross-correlate the different observations. We named this algorithm "Friends, and Friends of Friends" (F&FoF).

The basic idea is that observation  $A$  is a "friend" of observation  $B$  if the time between them is less than 14 days, the absolute difference between their Carrington heliographic longitudes is less than 5 degrees, and the absolute difference between their heliographic latitudes is less than 2 degrees.

The second rule is that if observation  $A$  is a "friend" of  $B$ , and  $B$  is a "friend" of  $C$ , then observation  $A$  is a "friend" of  $C$  too.

With this simple algorithm we found 486 different sunspots, each with strictly more than two observations for Carrington, 1071 for Peters, and 470 for de la Rue.

Carrington and Peters observed simultaneously from 23 May 1860 to 24 March 1861, and de la Rue's entire campaign lies within Peters' observation run. Using the same rules as the F&FoF algorithm, we cross-correlated the sunspots

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<sup>1</sup><http://ssd.jpl.nasa.gov/horizons.cgi>

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**Table 1.** Comparison between the heliographic coordinates observed simultaneously by Carrington and Peters, and by de la Rue and Peters. The value of  $\Delta$  used is the median of the differences in the observations in the sense Carrington/de la Rue minus Peters to avoid outliers, and the associated error is the standard deviation related to the MAD (see the text for the definition).

Observers	$\Delta L$ (degrees)	$\Delta B$ (degrees)
Carrington – Peters	$+0.19 \pm 1.55$	$-0.40 \pm 0.40$
de la Rue – Peters	$+0.52 \pm 1.16$	$-0.05 \pm 0.64$

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observed by each astronomer, finding 104 coincident groups between Carrington (21.4% of his total amount) and Peters (9.7%), and 157 between de la Rue (33.4%) and Peters (14.6%).

Table 1 lists the differences in the heliographic coordinates between the values measured by each pair of observers. This table uses the median and the standard deviation associated with the median absolute deviation ( $\sigma \approx 1.4826 \cdot MAD$ ) to avoid the outliers. For both pairs of observers, the differences between their heliographic longitude and latitude measurements were less than  $1\sigma$  in absolute value, allowing one to conclude that the coordinates obtained are compatible.

#### 4. Solar rotation velocity with the sunspots as tracers

Once we had identified the observations of the same group with the algorithm described in the previous section, we determined the mean Carrington heliographic coordinates ( $L, B$ ) for each group and their standard deviations ( $\Delta L, \Delta B$ ).

We determined the Stonyhurst heliographic longitude  $L_{Stn}$  values for each observation using the respective Horizons ephemeris (Giorgini *et al*, 1996) and the Carrington longitudes  $L_{Car}$ .

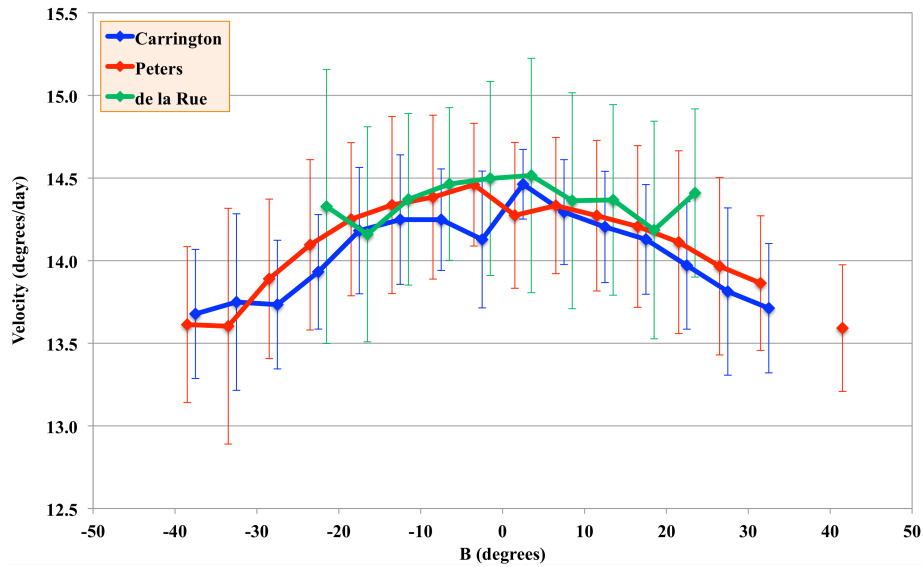
To determine the synodic rotation velocity ( $\omega_{syn}$ ), we performed a linear regression of the Stonyhurst longitude for each group on the observation time  $L_{Stn} = a + \omega_{syn} \cdot t$ . From the fit, we also evaluated the meridian transit time ( $t_0$ ) that we used to determine the velocity correction to apply in obtaining the sidereal velocity ( $\omega_{sid}$ ).

Although the dependence of the rotational velocity on the heliographic latitude is known, we used the median and the standard deviation associated with the MAD to reject outliers with values beyond  $3\sigma$ . For Carrington, Peters, and de la Rue, this resulted in 15 (3.1% of the full set of groups), 47 (4.4%), and 60 (12.8%) values being rejected, respectively. The large fraction rejected of de la Rue's data is because of the large scatter of the sample (see CV14).

The representation of the sidereal velocity as a function of the heliographic latitude shows a major scatter. It is usual to consider the average values of bins of latitude values. We chose latitude bins of 5 degrees width. Figure 1 shows the results for the three observers. The figure does not include the bins with only

**Table 2.** Differences between the rotational velocities observed simultaneously by Carrington and Peters, and by de la Rue and Peters. The value of  $\Delta\omega$  used is the median of the differences in the observations in the sense Carrington/de la Rue minus Peters' observations to avoid outliers, and the associated error is the standard deviation related to the MAD (see the text for the definition).

Observers	$\Delta\omega$ (degrees/day)
Carrington – Peters	$-0.11 \pm 0.29$
de la Rue – Peters	$-0.03 \pm 0.45$



**Figure 1.** Averaged sidereal velocities of Carrington, Peters, and de la Rue in bins of 5 degrees latitude width. For the sake of clarity, Peters' observations are shifted +1 degree in latitude B, and de la Rue's are shifted -1 degree.

a single measurement, and, for the sake of clarity, Peters' heliographic latitudes are shifted +1 degree and those of de la Rue -1 degree.

Table 2 lists the mean velocity differences determined from the cross correlations between the sunspot groups observed by two observers simultaneously. One notes that these values do not reflect any differences between the rotational velocities calculated by each astronomer.

## 5. Differential rotation law

Various authors (Newton and Nunn, 1951; Ward, 1966; Tang, 1981; Howard, Gilman, and Gilman, 1984; Balthasar, Vázquez, and Wöhl, 1986; Zappala and

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**Table 3.** The observers' data fitted to an  $\omega = a + b \cdot \sin^2 B$  law.

Observer	a (degrees/day)	b (degrees/day)
Carrington	$14.344 \pm 0.029$	$-2.555 \pm 0.231$
Peters	$14.410 \pm 0.024$	$-2.233 \pm 0.220$
de la Rue	$14.455 \pm 0.046$	$-2.027 \pm 0.760$

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Zucarello, 1991; Casas, Vaquero, and Vázquez, 2006) have used the differential rotation law  $\omega = a + b \cdot \sin^2 B$  to fit the dependence of the rotational velocity on the heliographic latitude when sunspots are used as tracers in different observation sets. The term  $a$  denotes the sidereal rotation velocity for the solar equator.

Table 3 lists the values we obtained using this law. The differential rotation laws deduced from Peters' and de la Rue' observations are compatible at a  $1\sigma$  level. Note that the two astronomers observed simultaneously. While the Carrington data give an equatorial rotation velocity that is somewhat lower, it still lies within the  $3\sigma$  interval.

For comparison, the differential rotation laws obtained by other authors are listed in Table 4.

## 6. De la Rue sunspot areas and rotational velocities

Table II of de la Rue, Steward, and Loewy (1869, 1870) lists the penumbral, umbral, and total areas measured for each sunspot group. Those data are probably the first published values of these quantities. Note that Vaquero et al. (2005) determined average values of the sunspot group penumbral-to-umbral area ratio from these early observations by de la Rue from the years 1862 to 1866 that were similar to the values reported by Hathaway (2013) for the period 1874–1976 using the sunspot catalogue of the Royal Observatory, Greenwich.

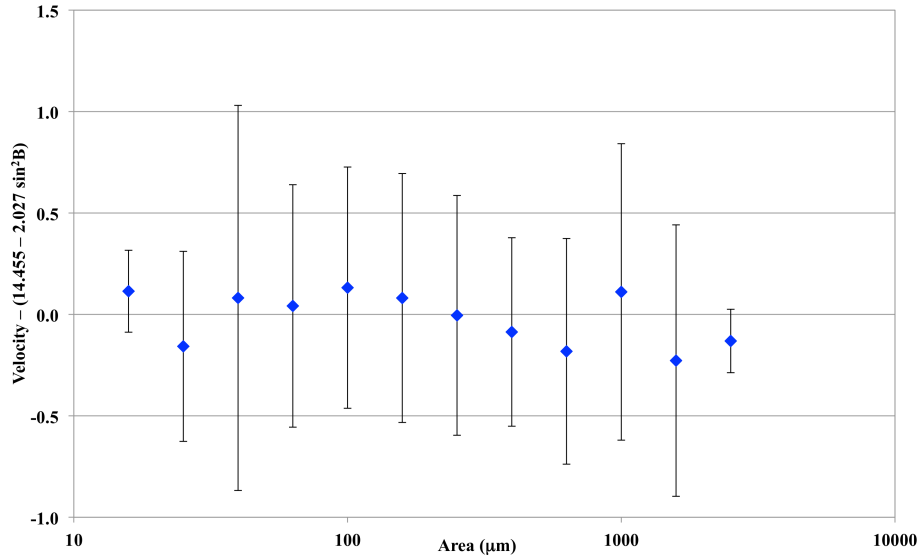
Ward (1966) and Howard, Gilman, and Gilman (1984) studied the relationship between the rotational velocity of a sunspot group and its maximum area. We analysed this correlation in the data of de la Rue, Steward, and Loewy (1869, 1870). We did not consider the absolute rotational velocity because of its dependence on the heliographic latitude. Instead, we considered the difference between the rotational velocity evaluated for each sunspot group and the differential velocity calculated using the coefficients given in Table 3. To this end, we took a logarithmic scale for the areas and split them into twelve equal width bins on that scale, and then averaged the velocities in each of those bins. The results are shown in Figure 2. One observes in the figure that the differences do not depend on the area, the mean value being  $\Delta\omega = -0.04 \pm 0.10$  degrees/day.

**Table 4.** The differential rotation law obtained by other authors with different data sets and fitted to an  $\omega = a + b \cdot \sin^2 B$  law.

Author/s Observation set	a (degrees/day)			b (degrees/day)		
Newton and Nunn (1951) GPR (1878 – 1944)	14.377	±	0.006	−2.77	±	0.08
Ward (1966) GPR (1905 – 1954)	14.523	±	0.006	−2.69	±	0.06
Eddy, Gilman, and Trotter (1977) Scheiner (1625 – 1626)	14.37	±	0.04	−0.90	±	0.62
Eddy, Gilman, and Trotter (1977) Hevelius (1642 – 1644)	14.94	±	0.12	−4.75	±	3.33
Herr (1978) Harriot (1611 – 1613)	14.58	±	0.12	−2.22	±	1.22
Abarbanell and Wöhl (1981) Hevelius (1642 – 1644)	14.58	±	0.07	−3.71	±	1.43
Yallop <i>et al.</i> (1982) Scheiner (1625 – 1626)	14.24	±	0.03	−2.42	±	0.32
Yallop <i>et al.</i> (1982) Hevelius (1642 – 1644)	14.47	±	0.03	−2.27	±	0.95
Howard, Gilman, and Gilman (1984) Mt. Wilson (1921 – 1982)	14.522	±	0.004	−2.84	±	0.04
Balthasar, Vázquez, and Wöhl (1986) GPR (1874 – 1976)	14.551	±	0.006	−2.87	±	0.06
Ribes, Ribes, and Bartholot (1987) Paris (1660 – 1719)	14.22	±	0.07	−8.34	±	0.89
Zappala and Zucarello (1991) GPR (1874 – 1976)	14.643	±	0.015	−2.24	±	0.16
Nesme-Ribes, Ferreira, and Mein (1993) Meudon (1974 – 1984)	14.47	±	0.07	−2.00	±	0.31
Nesme-Ribes, Ferreira, and Mein (1993) Mt. Wilson (1974 – 1984)	14.49	±	0.02	−2.60	±	0.15
Gupta, Silvaraman, and Howard (1999) Kodaikanal (1906 – 1987)	14.456	±	0.002	−2.89	±	0.02
Casas, Vaquero, and Vázquez (2006) Galileo (1612)	14.42	±	0.11	−4.96	±	1.40

## 7. Conclusions

Solar rotation is an important parameter in trying to understand our Sun. There is little information available on solar rotation in the 19th century, however. We have tried to contribute to improving this situation by studying the sunspot catalogues published by Carrington, Peters, and de la Rue in that century, covering the period 1853–1870. We have determined the rotational velocity for each sunspot group identified in those catalogues. From our findings, we would highlight three results:



**Figure 2.** Averaged sunspot group difference between the rotational velocities fitted for each group minus the differential velocity law fitted with de la Rue's data, with the averages taken over equal width bins of area on a logarithmic scale. The distribution shows behaviour that is constant with area. The mean value is  $-0.04 \pm 0.10$  degrees/day.

(i) We found no differences in rotational velocity between sunspot groups that were observed simultaneously by two observers.

(ii) Fitting a differential rotation law ( $\omega = a + b \cdot \sin^2 B$ ), we found no differences between Peters' and de la Rue's observations. There was, however, a slightly lower value for  $a$ , the rotational velocity at the equator, for Carrington's observations. There were no differences between the values of  $b$ , the coefficient of the term that depends on the latitude, considering the error bars.

(iii) Finally, we found no differences in the rotational velocity between small groups and large groups using the sunspot data published by de la Rue, Steward, and Loewy (1869, 1870).

This work was made possible by the recovery of three sunspot catalogues published in the 19th century. The study and merging of historical sunspot catalogues should contribute to our better understanding the state of the Sun in the last two centuries at least (Lefevre and Clette, 2014; Carrasco, et al., 2014).

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<sup>2</sup><http://www.tosca-cost.eu>



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